The formation of the rare earth peak during the r-process

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The r-process

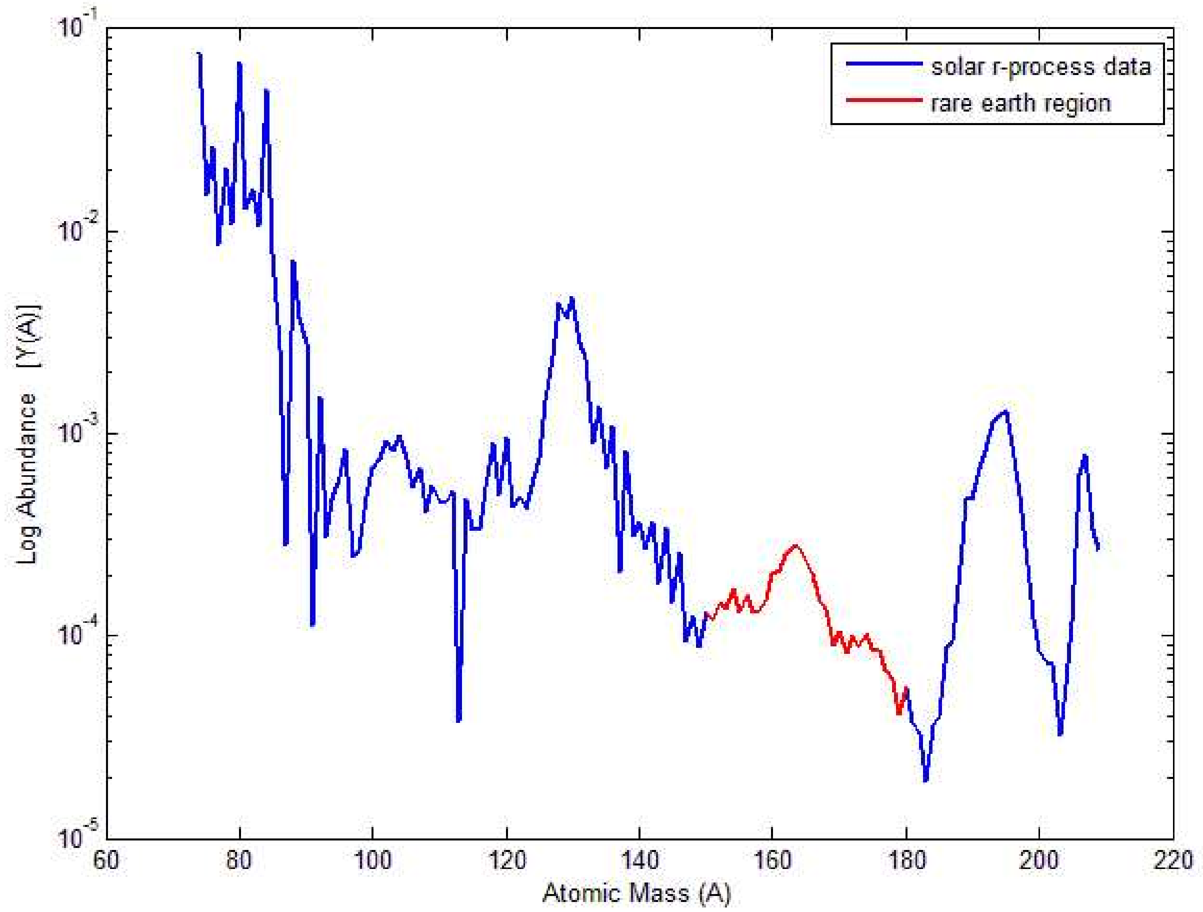
The r-process is responsible for many heavy nuclei including the actinides.

Three reactions are primarily important in the r-process: neutron capture, beta-decay and photodissociation.

“hot” r-process: all three reactions are important → (n,γ), (γ, n) equilibrium is obtained along an isotopic chain for much of the r-process

“cold” r-process: photodissociation is not important

The rare earth peak



Solar abundance data with the rare earth peak in red

Calculations of r-process abundances

Procedure:

- select astrophysical environment
- understand or guess at thermodynamic conditions, i.e. temperature, density, initial neutron to proton ratio
- check neutron to seed ratio
- perform network calculation and see how (and if) the neutrons capture on the seeds

Where is the r-process formed?

We don't know! Why? Can't find a theoretically self-consistent and robust model that fits all data. Best options:

- Core collapse supernovae
- Compact object mergers

Supernovae: halo star data hints are supernovae, but models problematic (not enough neutrons)
Mergers: models in a bit better shape, but timescale problematic

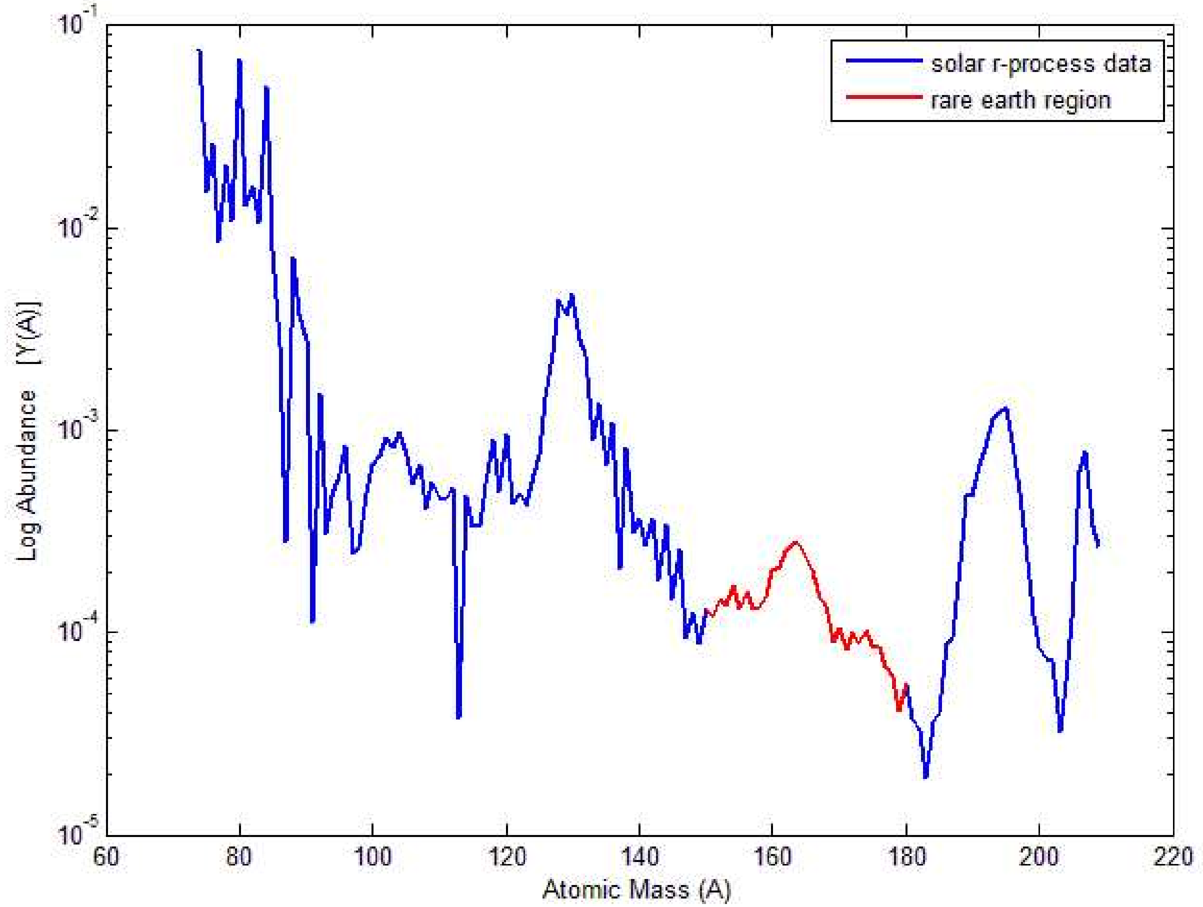
Discussion has focused on finding an environment that occurs with high frequency and produces the correct neutron to seed ratio (sometimes called the problem of high enough entropy).

Beyond the neutron to seed ratio

Halo stars: “main” or large Z part of the pattern is a consistent shape Suggests: look for something that fits data (as opposed to just creating enough neutrons)

- major peaks at A=80, A=130, and A=195 exist generically because of closed shells
- for peaks, success depends on the neutron to seed ratio
- instead of major peaks, study rare earth peak formation which is sensitive to late time behavior
- late time means decay back to stability
- hope this can constrain late time dynamics and therefore the site of r-process

The rare earth peak



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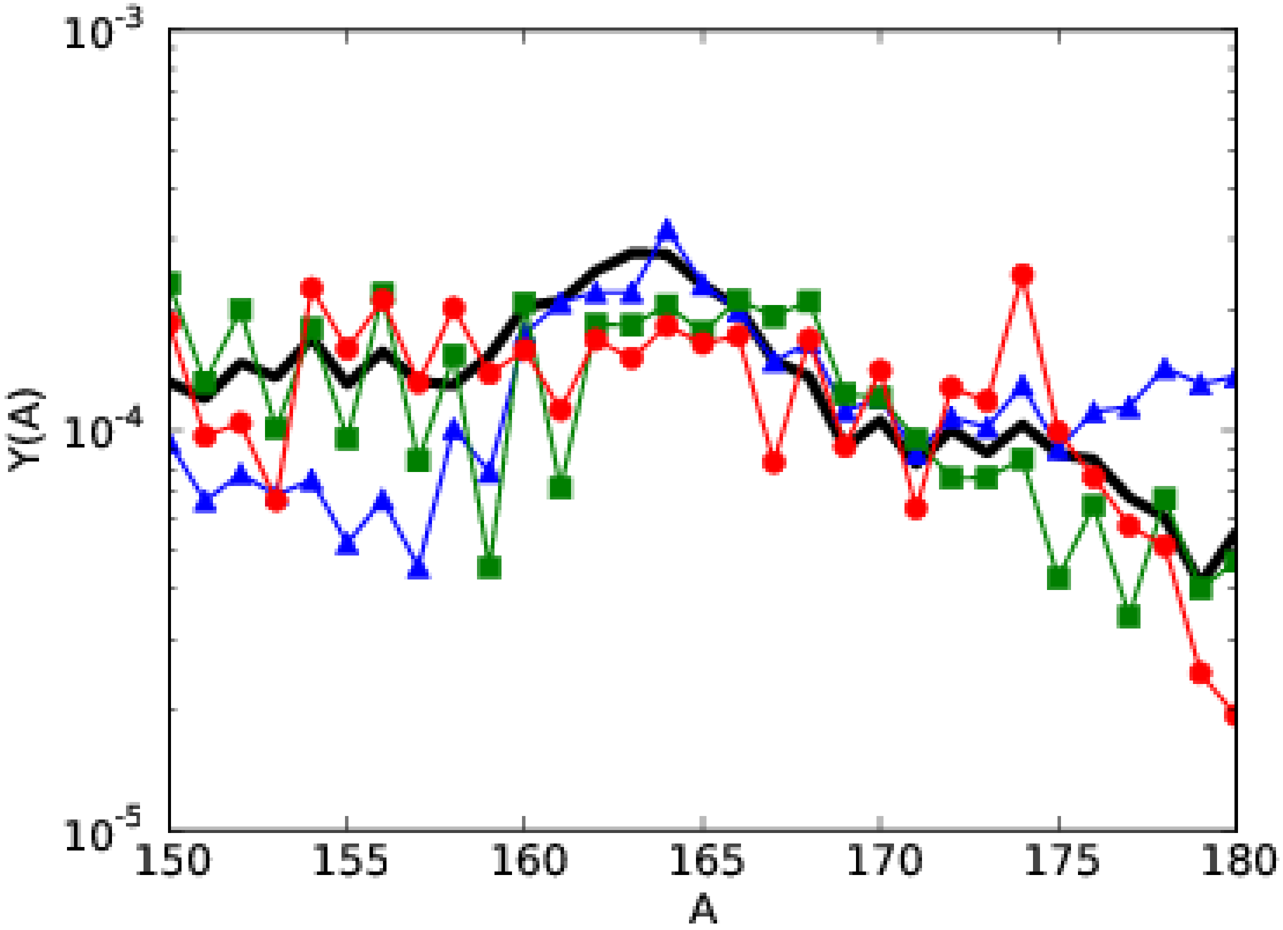
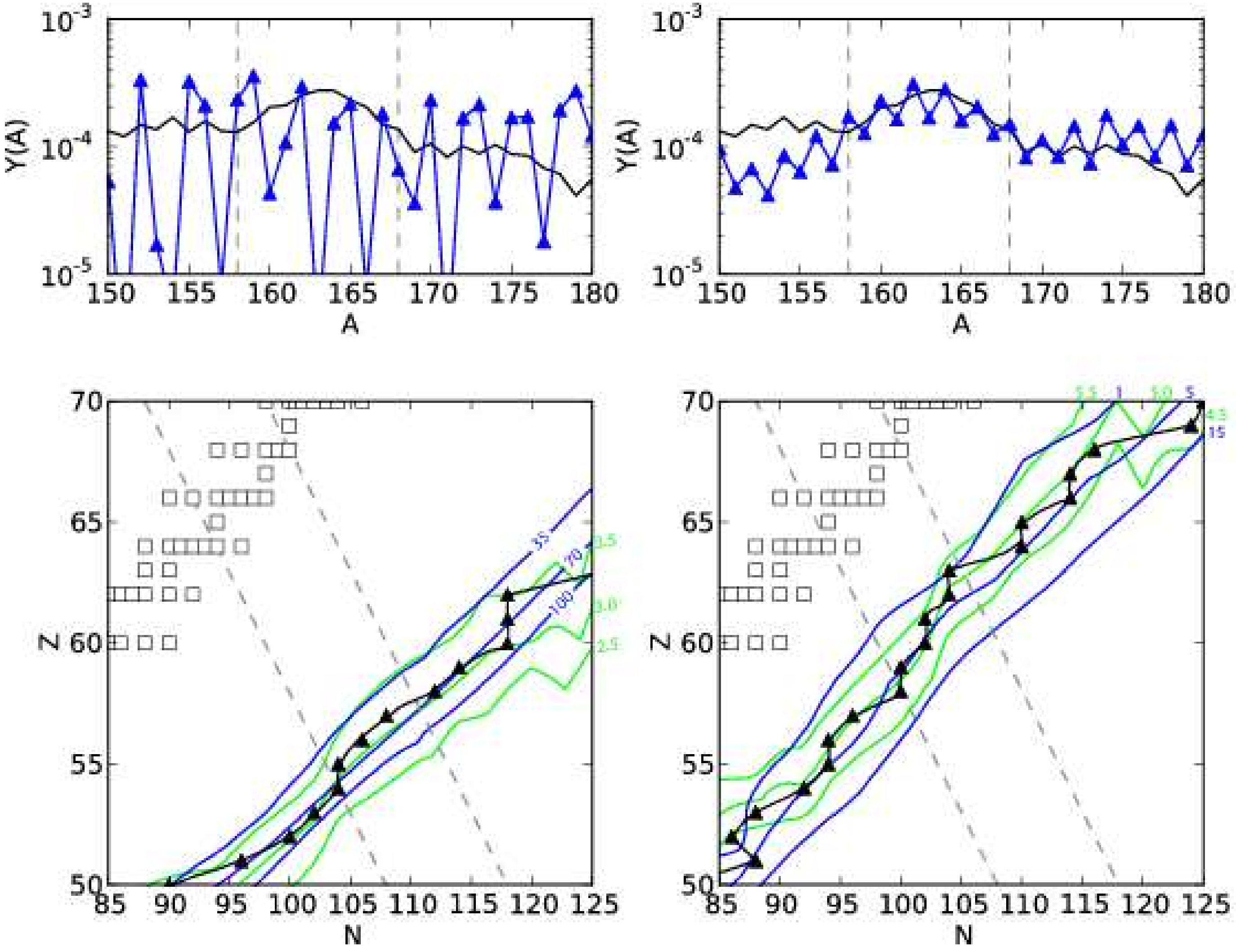
A few rare earth peak calculations



A few rare earth peak calculations with different mass models

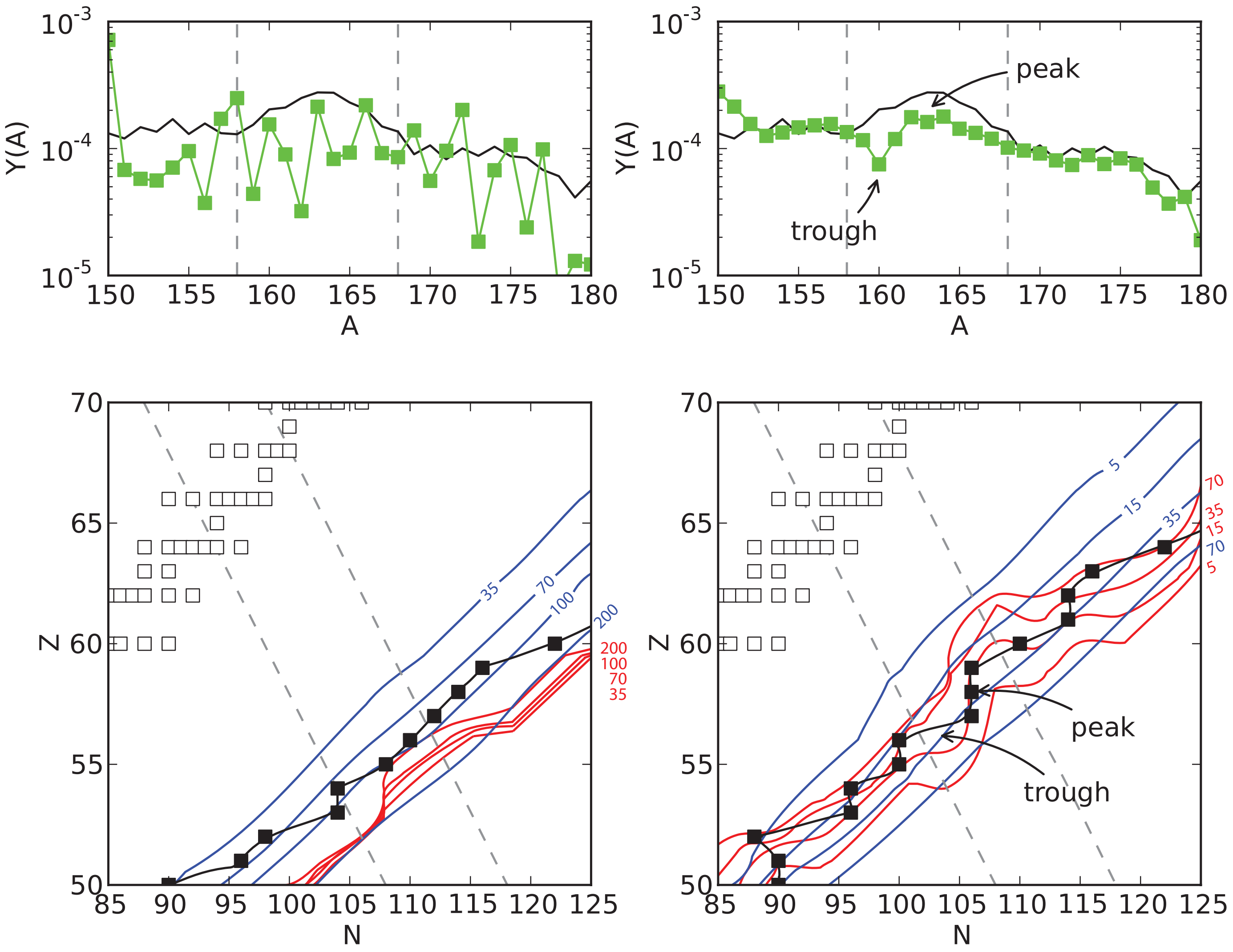
Hot rare earth peak formation

Surman and Engel 1997



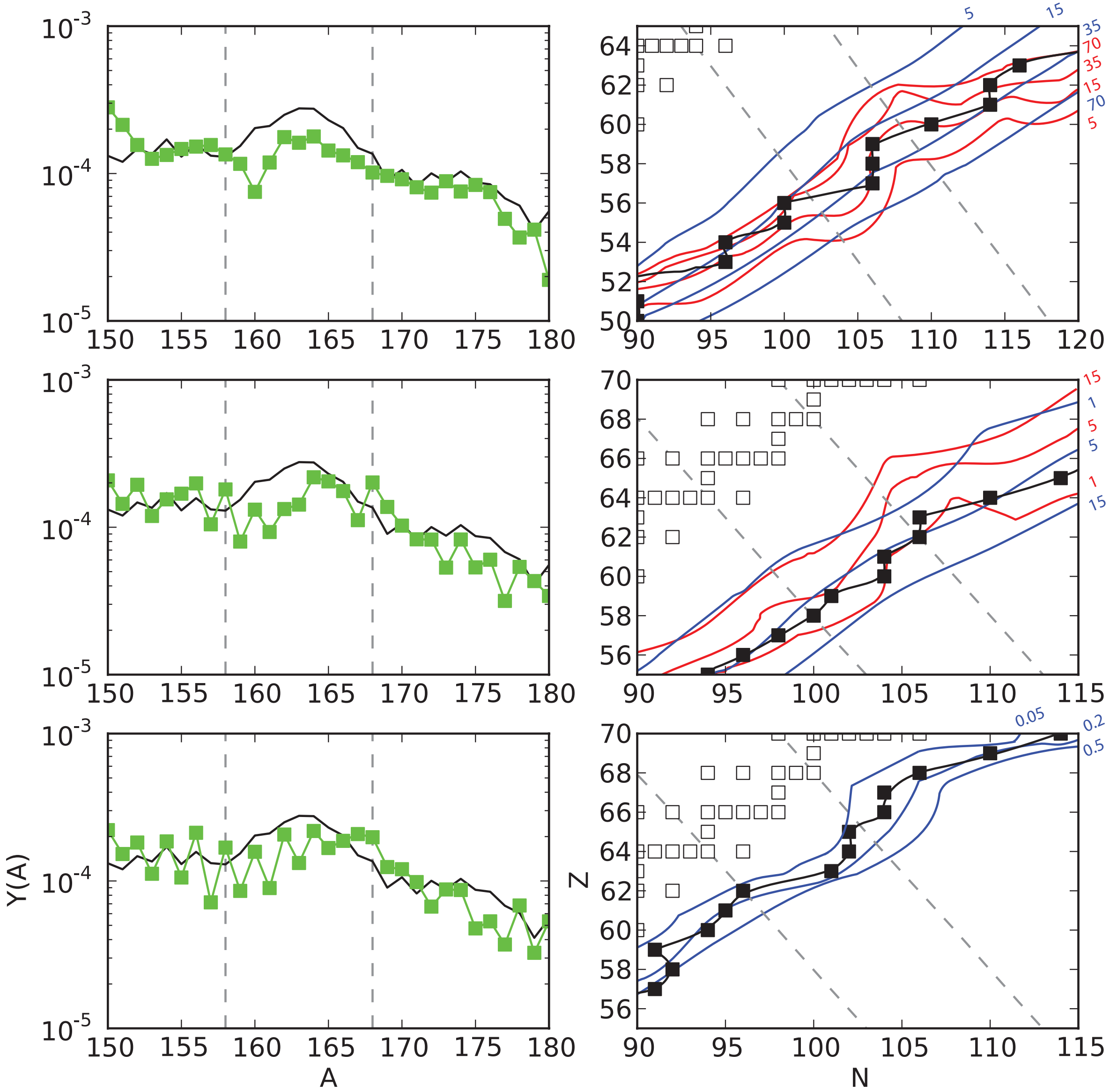
Neutron capture just below the peak and photo-dissociation above

How cold peaks form



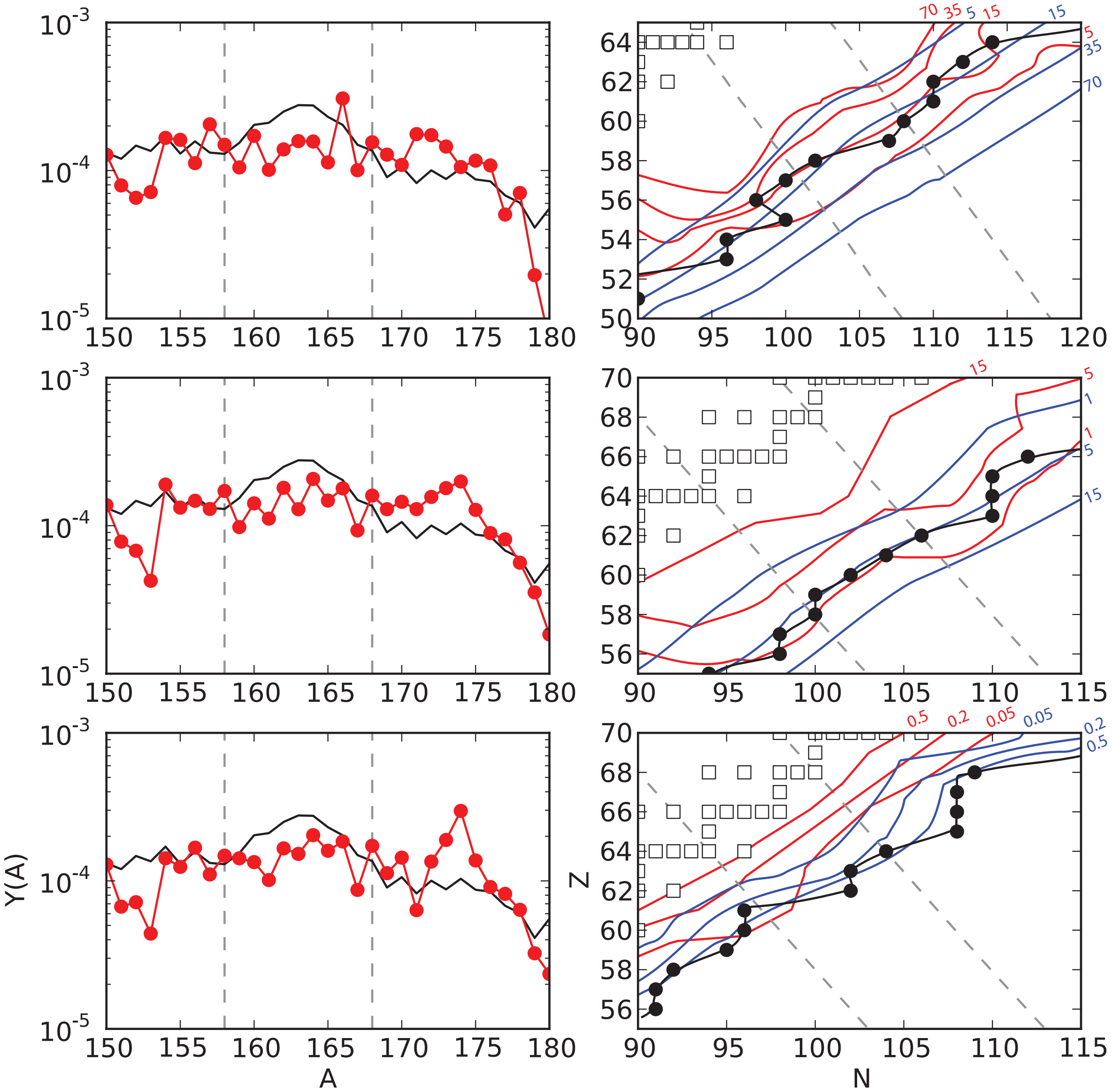
Neutron capture just below the peak and less neutron capture above

Peak evolution



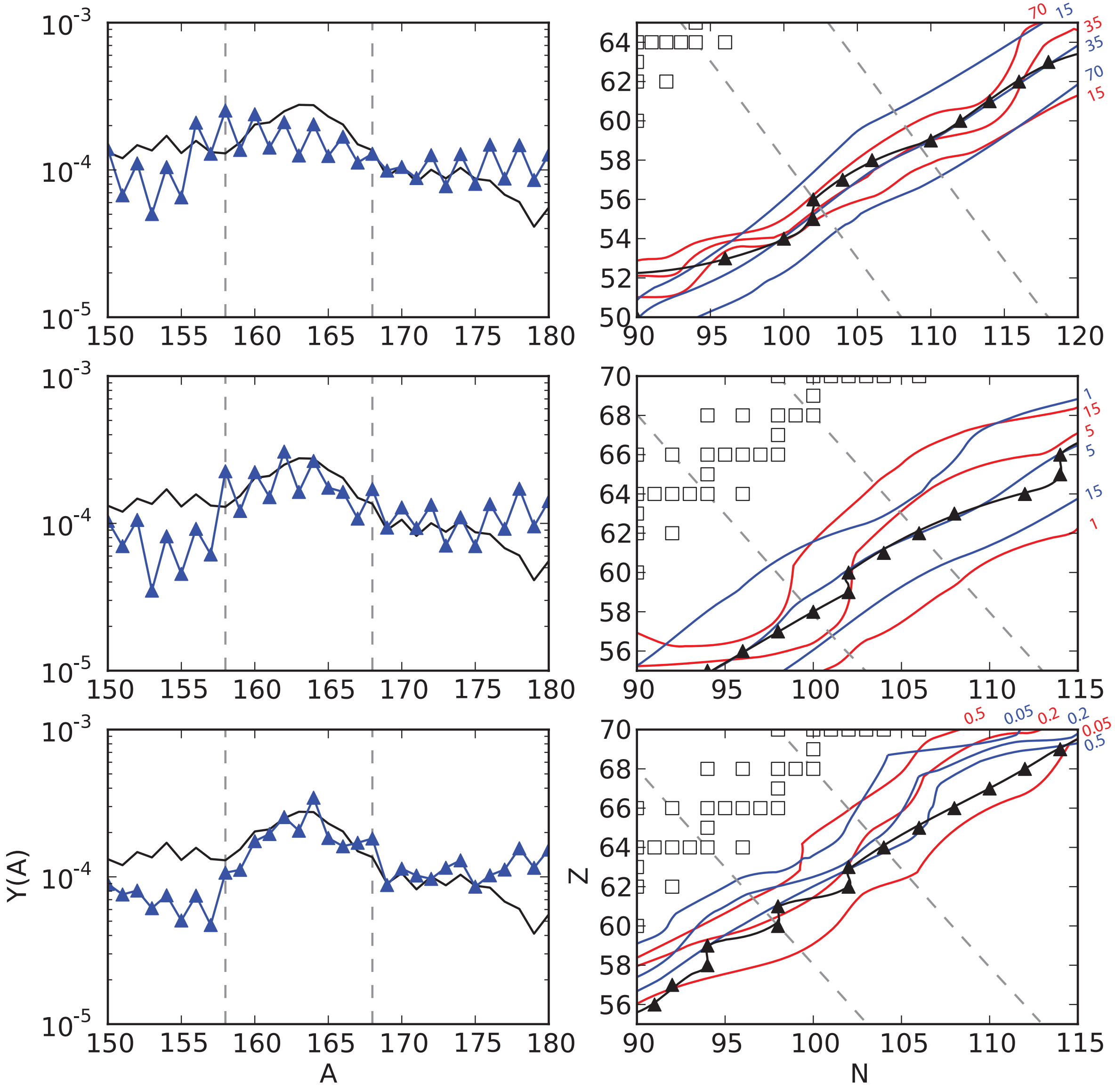
Calculation with the ETFSI model

Peak evolution



Calculation with the HFB17

Peak evolution



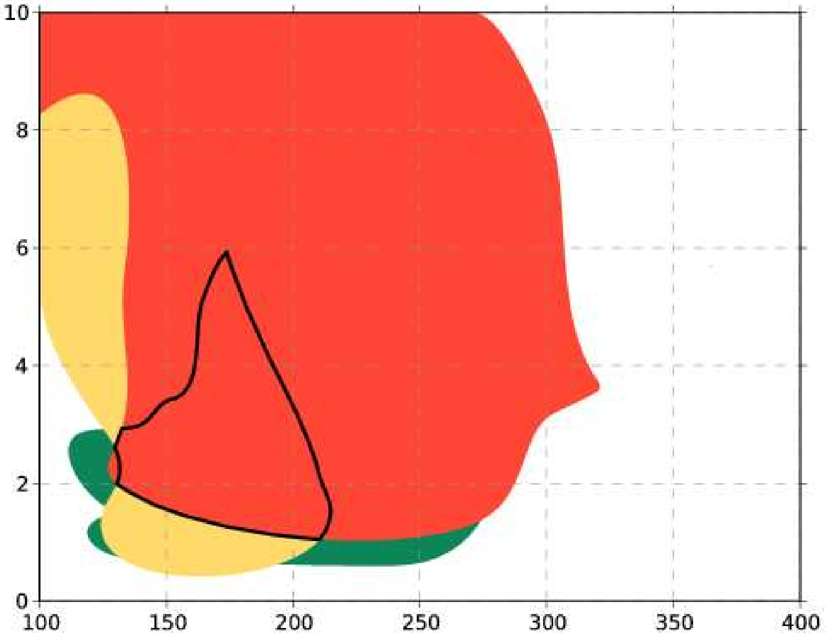
Calculation with the FRDM (finite range droplet model)

Can the rare earth peak be used to constrain the environment?

If the formation of the rare earth peak is delicate, then one should be able to use it to constrain the conditions during the r-process, i.e. beyond the neutron to seed ratio

- at $T_9 = 2$ start with a neutron to seed ratio (entropy)
- let the density fall as $\rho \propto t^{-n}$, and vary n, constant entropy fixes the temperature

Constraints on power law decay and entropy

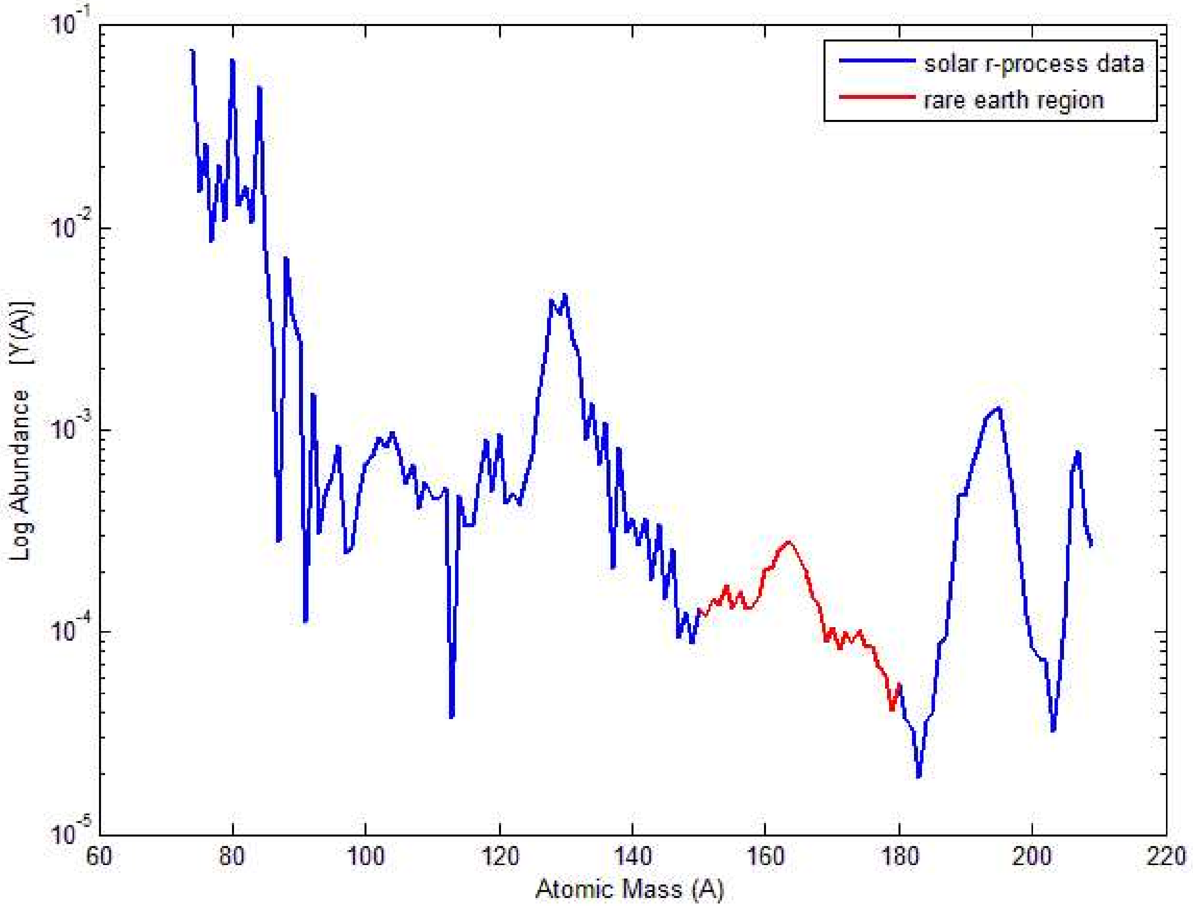


Entropy per baryon

- Red: ok rare earth shape
- Yellow: ok rare earth to A=195 ratio
- Green: not too much neutron capture on the sides of the peak e.g. Arcones

Calculation with the FRDM (finite range droplet model) using $Y_e = 0.3$

The rare earth peak



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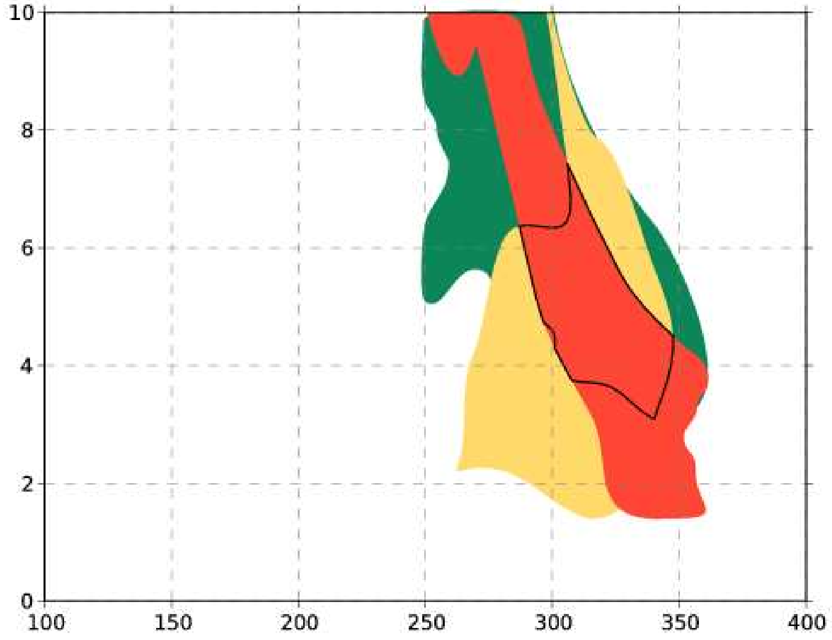
Constraints on power law decay and entropy



Entropy per baryon

- Red: ok rare earth shape
- Yellow: ok rare earth to A=195 ratio
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Calculation with ETFSI (Extended Thomas-Fermi) with $Y_e = 0.4$

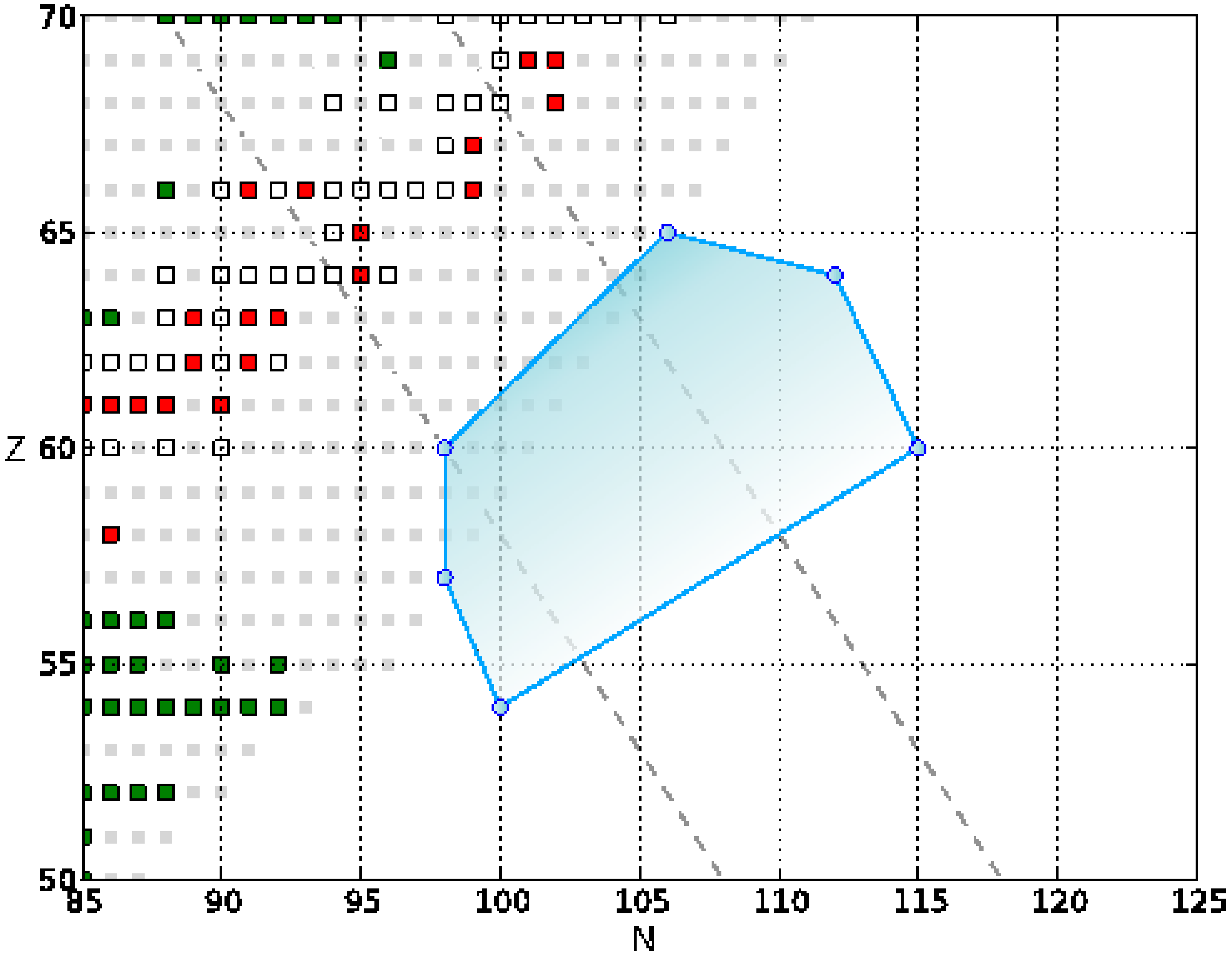
Can the rare earth peak be used to constrain the environment?

If the formation of the rare earth peak is delicate, then one should be able to use it to constrain the conditions during the r-process, i.e. beyond the neutron to seed ratio

In principle yes, we can determine at which rate the temperature and/or neutron density must decline in order to make a good rare earth peak.

But improvements in neutron capture rates and separation energies would provide better constraints

The nuclei that matter for the rare earth peak



Conclusions

- the rare earth peak can form even in the absence of photo-dissociation
- the rare earth peak can constrain conditions in way that is different than the using the neutron to seed ratio
- this would work much better if we understood better the neutron capture rates and separation energies of rare earth nuclei slightly away from stability